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Biofuels and their potential to aid the UK towards achieving emissions reduction policy targets

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ABSTRACT

The potential of biofuels contributing to the UK emission reduction targets in the formulated UK Low Carbon Transition Plan (LCTP) and the UK's obligation in the wider EU emissions reduction targets are assessed using four scenarios. The scenarios were evaluated using hybrid lifecycle assessment developed in a multi-regional input–output (MRIO) framework. In the hybrid MRIO LCA framework, technology-specific processes in the biofuels and fossil fuels LCA systems are integrated into a generalised 2-region (UK and Rest of the World) environmental-economic input–output framework in order to account for economy-wide indirect GHG emissions in the biofuels and fossil fuels LCA systems in addition to other indirect impacts such as indirect land use change. The lifecycle greenhouse gas emissions of biodiesel (soybean, palm, rape, waste cooking oil) and bio-ethanol (sugarcane, sugarbeet, corn) were assessed and compared to fossil fuel (diesel and petrol) baseline. From one of the scenarios, biodiesel production from waste cooking oil and bioethanol from sugarbeet offer the biggest potential for emissions savings relative to fossil fuel equivalent and offering a maximum emission savings of 4.1% observed with a biofuel market share of 10% reached in 2020. It was also established that under current biofuel feedstock mix, to achieve the 6% emissions saving primarily from biofuels as proposed in the LCTP, 23.8% of the transport fuels market would be required to be held by biofuels by 2020.

Contents

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1. Introduction

Faced with increasing emissions and ever more apparent impacts, governments are using legislation to expedite transitions towards a low carbon economy and to a lower carbon technology uptake. The European Union (EU) legislation drawn to encourage adoption and development of renewable technologies highlights the importance of transport fuels within the 20% renewable energy target in the overall EU energy mix by 2020 [1,2]. In 2000, a EU Green Paper entitled '*Towards a European Strategy for the Security of Energy Supply*' initiated the beginning of a more comprehensive policy in which biofuel was required to make a contribution in producing 20% of alternative fuel sources: bio-fuel, biogas and hydrogen by 2020. Of the three alternative sources, only the targets for biofuel initialised in the Green Paper was finally translated into the 2003 EU Directive (2003/30/EC): 'Directive on the promotion of the use of bio-fuels or other renewable fuels for transport'.

At the national level, the UK Low Carbon Transition Plan (LCTP) outlined in the 2008 UK White Paper aims to cut 18% of greenhouse gas emissions on 2008 levels by 2020 and over a third on 1990 levels over the same period. The decarbonisation of the transportation sector is among the strategic plans outlined by the UK government in the white paper. The UK, for which transport emissions account for circa 20% of total emissions [3] has hence, adopted EU Directives – enshrined into law by the climate change act – and aims to achieve 6% reduction in transport emissions [4–6]. The LCTP indicates that this 6% reduction in greenhouse gas emissions from transport fuels by 2020 would be achieved primarily through an increase in biofuel use to 5% of fuel blend by 2013–14 and 10% of UK transport fuel being sourced from renewable sources by 2020 and through other commitments such as Renewable Transport Fuel Obligation (RTFO) and EU Renewable Energy and Fuel Quality Directives.

To achieve proposed targets within the transport sector, UK legislation seeks to incentivise biofuels with tax exemptions and obliging supply through RTFO. Controversy, however, has arisen surrounding the sustainability of biofuels, with arguments presented that issues such as land-use change and threats to food supply chains [7] have not been fully considered and NOx emissions as a result of fertilizer use in bio feedstock cultivation underestimated [8,9]. The Gallagher report, which sought to address concerns, echoed the significance of land-use change and proposed a "slow down" on proposed targets [10]. Considering this, Gallagher et al. [10] purport that the "optimum policy approach" is basing incentives for biofuels upon their greenhouse gas (GHG) saving potential; further strengthening the imperative to reliably evaluate GHG emissions of biofuels.

Lifecycle analysis (LCA) is the established method utilised to yield meaningful emissions figures for products and services, with literature holding numerous examples [11–13]. LCA can essentially be undertaken by three methods: Process, Environmental Input–Output (EIO) or an integration of the two [14–16]. Process LCA is highly defined by ISO standards [17], working by creating a system boundary dictated by the aims of the study and accounting for individual emission contributions within the system. EIO on the other hand uses country and/or regional input–output data coupled with averaged sectoral emissions to calculate environmental impacts, yielding an all-encompassing result but having the drawback of being less specific due to aggregation of a range of activities in one sector [18] and the assumptions of proportionality and homogeneity [19]. Integration of the two methods via a hybrid method retains the specificity of process LCA with inclusive nature of EIO; hence hybrid LCA approaches can be implemented in practice for broadening system boundary and also for ISO compliance [20]. As shown by Crawford [21], Lenzen and Crawford [22] and Suh and Huppes [23], the use of hybrid LCA therefore ensures a systematically complete LCA system is achieved. Specifically, hybrid LCA places more emphasis on the process data, avoiding documented truncation, double counting issues incurred through other proposed methods and system boundary completeness [23–25];

Using Hybrid LCA within a multi-regional input–output (MRIO) framework similar to the one used in Wiedmann et al. [26] to account for indirect GHG emissions of wind power generation in the UK, this study aims to compare emission resulting from biofuel consumption, with respect to the fossil fuel baseline, explicitly quantifying whether proposed targets are achievable. Four scenarios are developed (using policy targets such as 10% market share of biofuel in transportation fuel [1] and 6% transport emissions saving in the UK by 2020 [4]) and assessed. These are: (1) current feedstock mix continuing and achieving 10% of transport fuel market by linear growth; (2) best case scenario (BCS), assuming biofuel which offers greatest GHG emission saving will dominate the market and achieve 10% market share; (3) the growth required, in terms of biofuel volume, to achieve the target 6% savings, based on current feedstock and market share by 2020; (4) the growth required to achieve the target 6% emissions savings, based on BCS by 2020.

2. Methodology, data and scenarios

2.1. Hybrid LCA

This work adopts the hybrid LCA methodology which is an integration of the traditional (or process) LCA and EIO LCA methods. Crawford [27] has demonstrated the novelty of hybrid LCA

approaches in the applications to building case studies, transport infrastructure and renewable energy technology case studies. In this paper, the integrated hybrid LCA methodology is used because it has a consistent and robust mathematical framework [23,26,28,29]. In this hybrid LCA approach, the MRIO matrix is interconnected with the matrix representation of the physical product LCA system. As a result, in the upstream and downstream inputs into the LCA system, where LCA data are missing (or, alternatively, LCA data quality is not satisfactory), EIO estimates are used [23]. A detailed explanation of the hybrid LCA methodology is provided in literature [26,29]. For instance, Acquaye et al. [29] applied the methodology and structural path analysis for decomposing the supply chain of rape methyl ester biodiesel; through a similar methodology, Wiedmann et al. [26] computed the indirect GHG emissions of wind power generation in the UK.

As shown by Suh and Huppes [23], the mathematical basis for the integrated hybrid LCA is given by:

$$\text{Emissions Impact} = \begin{bmatrix} E_p & 0 \\ 0 & E_{i-o} \end{bmatrix} \begin{bmatrix} A_p & -D \\ -U & (I - A_{i-o}) \end{bmatrix}^{-1} \begin{bmatrix} y \\ 0 \end{bmatrix}$$

where A_p is the square matrix representation of process inventory, (dimension:s $\times$ s); A_{i-o} the MRIO technology coefficient matrix (dimension:m $\times$ m); I the identity matrix (dimension:m $\times$ m); U the matrix representation of upstream cut-offs to the process system (dimension:m $\times$ s); D the matrix of downstream cut-offs to the process system (dimension:s $\times$ m); E_p the process inventory environmental extension matrix. CO_2-eq emissions are diagonalised (dimension:m $\times$ s); E_{i-o} the IO environmental extension matrix. CO_2-eq emissions are diagonalised (dimension:m $\times$ s); $\begin{bmatrix} y \\ 0 \end{bmatrix}$ the Functional unit column matrix with dimension (s+m,1) where all entries are 0 except y.

Matrix A_p describes the product inputs into processes as captured in the process analysis matrix. A_{i-o} is a (896x896) multi regional input–output (MRIO) supply and use technology matrix describing a network of input and output coefficients requirements from one sector to another within the UK-Rest of the World-IO framework. Matrix U, which is assigned a negative sign represents the higher upstream inputs from the IO system to the process system. Matrix D, also assigned a negative sign, represents the (downstream) use of goods/inputs from the process system to the background economy (IO system). The negative signs represent the direction of flow of inputs.

2.2. LCA data

2.2.1. Multi-region input–output (MRIO) framework

The input–output tables used in this study are the MRIO tables represented by a two region supply and use tables for the UK and Rest of the world. Wiedmann et al. [26] describes in detail the construction of the MRIO technology coefficient matrix, A_{i-o} maintaining the representation of supply and use tables' structure and also of Matrix D and Matrix U.

2.2.2. Process data

The matrix representation of the physical process inventory was constructed using 2010 v2.2 ecoinvent unit process raw data [30]. Some of the very relevant unit process raw data obtained were:

- for biodiesel: (bio-feedstocks, chemicals such as methanol and phosphoric acid used in the esterification process, electricity, natural gas, road and rail transportation, etc.)
- for bioethanol: (bio-feedstocks, chemicals, electricity, natural gas, road and rail transportation, etc.).

The datasets selected were preferentially from countries or region from which majority of UK biofuel by feedstock are imported. The cumulative impact assessment results from ecoinvent (LCIA) for greenhouse gas (GHG) warming potential were taken over a 100 year period, due to relevance to current legislative goals [31].

2.2.3. Other sources

To establish the fossil fuel baseline, calculated LCA results for petrol and diesel were combined with combustion emission data obtained from the Department for Environment, Food and Rural Affairs (DEFRA) [32]. UK consumption data for biofuels and fossil fuels were obtained from the Renewable Fuel Agency and Department for Transport [33–35]. Unit prices used in calculating upstream inputs (refer to [26,29]) were taken from the Products of the European Community (PRODCOM) database [36]. Indirect land-use Change (iLUC) factors were used based on previous work by the Institute for Applied Ecology [37].

2.3. Scenarios development

2.3.1. Baseline

This shows resultant emissions if transport fuels are considered entirely from fossil fuels (diesel and petrol). Baseline figures were obtained as the product of consumption and total LCA emissions, where total LCA emissions are considered to be the sum of process, upstream and use (combustion). Combustion emissions were obtained from DEFRA [32]. Consumption from 2010 is assumed to be constant. The difference between this baseline and scenario's potential emissions therefore yields the potential emissions savings.

2.3.2. Scenario 1: Emissions savings based on current biofuel market share

Scenario 1 shows the emissions from biofuels based on the current market share. Using 2005–2009 transport fuel consumption data from DECC [35], market shares reported by the Renewable Transport Fuel Obligation (2010) [38] and Renewable Fuel Agency (2008–2009) [34] and combined with calculated feedstocks' LCA emissions the preceding four years' transport fuel GHG emission were calculated. Scenarios emissions for each year is calculated as the product of consumption and respective LCA results, and potential savings are with reference to the supplemented or substituted fuel; biodiesel for diesel and bioethanol for petrol. Then using the more recently available data on market and feedstock share, assuming constant transport fuel consumption and constant biofuel mix; potential emissions savings were forecasted until 2020 assuming linear growth of biofuel consumption to the 10% volume target.

2.3.3. Scenario 2: Best case scenario (BCS) emissions savings

Presuming legislative goals of reducing emissions are sought; Scenario 2 illustrates the maximum transport fuel emission savings. Using the same initial data as Scenario 1, Scenario 2 selects the biodiesel and bioethanol feedstock that offer the greatest GHG savings and scales them to equate for total market share; exemplifying the significance of feedstock in terms of emissions savings.

2.3.4. Scenario 3: Assuming current market share, what % biofuel is required to achieve 6% emission savings?

With current market share assumed constant, Scenario 3 shows the % share required to meet the 6% reduction goal anticipated in the LCTP. Using the same initial data as in Scenario 1, the linear growth is calculated to meet the required emission savings.

2.3.5. Scenario 4: Assuming BCS, what % of biofuel is required to achieve 6% emission savings?

Scenario 4 demonstrates the lowest % biofuel market share required to meet the 6% emissions savings target, based on BCS in terms of feedstock. The same data as in Scenario 2 was extended to show the linear growth required to meet the goal.

2.4. Assumptions

LCA, by its nature, requires assumptions and caveats upon analysis and results; temporality, spatial differences, intermediacy and plurality of sources dictate this.

- The temporal issues arise from time for collection of lifecycle inventories, datasets are therefore assumed to accurately represent current processing. Spatially, datasets differ in location which may result in different LCA outcomes. In this study the spatial choice of LCA data was based on the country (or region) from which the majority of UK biofuel by feedstock were imported. Refer to Table 1.
- Accounting for vehicle operation is technically challenging, highly technology dependant and therefore can introduce error; by assuming similar contributions, it is possible to exclude this from the study.
- The carbon released through combustion of biofuels is biogenic CO_2; this was captured in the process LCA ecoinvent data [39]. It was calculated using the principle of carbon balance (input of carbon = output of carbon); that is, the uptake of carbon during plant growth plus all inputs of biogenic carbon with all pre-products minus biogenic carbon emissions should equal the biogenic carbon content of the biofuel or the product after all allocations have been done. The carbon released through fossil fuel combustion is from carbon stores outside the time horizon and therefore is included. However, N_2O emissions occur during combustion and ideally should be included, but are outside the scope of this study.
- Price estimates required to derive upstream requirements that link the process LCA system to MRIO were obtained from UK PRODCOM database. It is acknowledge that basic price fluctuation may occur but this is assumed to have little impacts on the results.
- In this study biofuels are assumed to be grown on arable, therefore have no direct land-use emissions. However, due to displacement risks highlighted by other studies, including Gallagher et al. [10] all indirect land use changes are considered to be of highest risk.
- The functional unit adopted in this study 1 kg CO_2-eq per. In the case of biofuels, the emissions are adjusted by energy content of the fuel they would supplement or substitute to yield the equivalent consumption.
- A static Input–Output model is used to analyse the dynamic development of different biofuel production technologies under different scenarios. Although this allows for the evaluation of indirect environmental impacts, it does not account for indirect economic effects as a result of changes in other sectors supplying production inputs to the biofuel sector. It is assumed that these indirect economic changes will be subtle; hence the changes in the production requirements of the biofuel sector from other sectors over time will be minimal. Evaluating the impacts of technological and production requirement changes using dynamic input–output analysis however is worth further research after the work by Wilting et al. [40] and Turner et al. [41] and on scenario analysis by Turner et al. [42].

3. Results

3.1. LCA results

Hybrid LCA was performed as discussed in section 2, with land-use and use phase summated post-hybrid LCA calculation. The hybrid LCA is calculated as the sum of the process and indirect upstream emissions. Results are shown in Table 2 and graphically presented in terms of litres adjusted to energy content in Fig. 1.

3.2. Scenario results

3.2.1. Baseline scenario results

The total LCA emission calculated for diesel and petrol are, respectively, 3.14 and 3.04 kg CO_2-eq/L (Fig. 1). The baseline scenario is determined by assuming that the total emissions from total UK consumption of transportation fuel are all fossil fuel

Table 1
Dataset temporal information, extracted from Ecoinvent [26].

Fuel type	Dataset	ISO Alpha-2 country code	Time period	Most recent timestamp	Time period information
Bio-diesel	Soybean	BR	1996–2006	2006	Data from 1996 to 2003, current technology for large scale biodiesel plants worldwide
	Rape	RER	1996–2006	2006	Data from 1996 to 2003, current technology in the EU
	Palm	MY	1996–2006	2006	Data from 1996 to 2003, current technology for large scale biodiesel plants worldwide
Fossil	Diesel	RER	1980–2000	2003	Statistical data for the throughput and production volumes were available for the year 2000. Major indicators like energy use have been estimated based on a survey in European refineries. Other data and indicators have been estimated based on different environmental reports.
	Petrol, unleaded	RER	1980–2000	2003	Statistical data for the throughput and production volumes were available for the year 2000. Major indicators like energy use have been estimated based on a survey in European refineries. Other data and indicators have been estimated based on different environmental reports.
Bio-ethanol	Sugarcane	BR	1994–2006	2006	Data from 1994 to 2006, current technology for the production of ethanol from sugarcane
	Sugarbeet	CH	2000–2004	2006	Production of ethanol from sugar beets with extraction, fermentation, and distillation of ethanol.

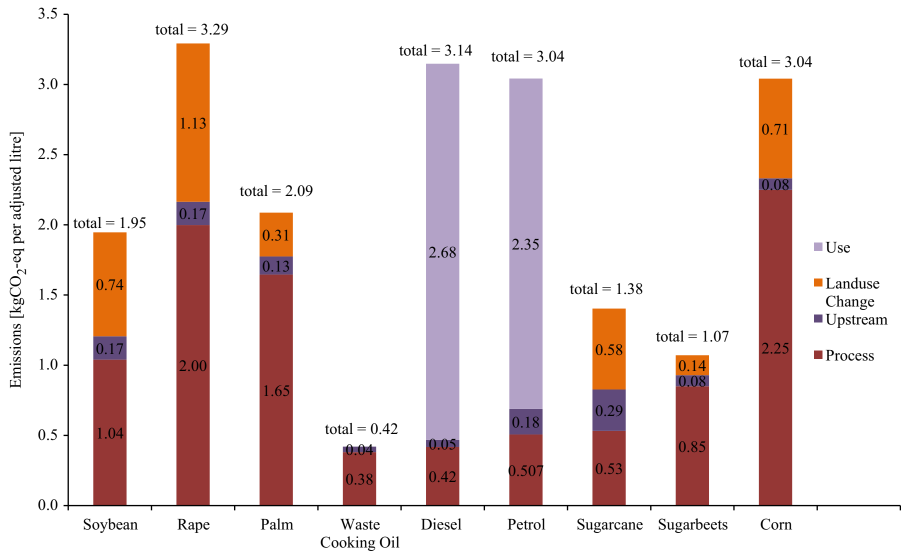

Fig. 1. LCA emissions of biofuels study and the baseline emissions of equivalent fossil fuels.

Table 2
Summary of GHG emission results from LCA study, in units of energy.

Fuel	Feedstock	Process emissions/kg CO_2-eq/GJ	Upstream emissions/kg CO_2-eq/GJ	iLUC/kg CO_2-eq/GJ	Use emissions/kg CO_2-eq/GJ	Total LCA emissions/kg CO_2-eq/GJ	Emissions per Aajusted litre/kg CO_2-eq/adj.L	Emissions saving [%]
Bio-diesel	Soybean	28.9	4.6	20.6	0.0	54.1	1.9	38.0
	Rape	55.5	4.6	31.3	0.0	91.5	3.3	−4.9
	Palm	45.7	3.6	8.7	0.0	58.0	2.1	33.5
	Waste cooking oil	10.6	1.1	0.0	0.0	11.7	0.4	89.4
Fossil	Diesel	11.3	1.4	0.0	74.4	87.2	3.1	–
	Petrol, unleaded	15.8	5.7	0.0	73.5	95.0	3.0	–
Bio-ethanol	Sugarcane	15.9	9.2	18.0	0.0	43.1	1.4	54.6
	Sugarbeet	26.6	2.5	4.4	0.0	33.5	1.1	64.8
	Corn	70.3	2.6	22.2	0.0	92.9	3.0	0.0

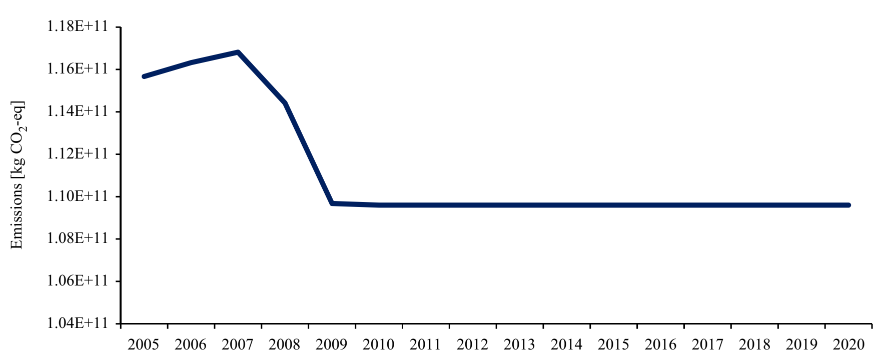

Fig. 2. Baseline emissions against time for UK transport fuels if all attributed to diesel and petrol.

[33,35]. Refer to Fig. 2. Total lifecycle emissions increased from 2005, peaking in 2007 but decreased thereafter. This followed the UK consumption trend of transport fuel. Consumption trend in the baseline scenario is assumed to be constant from 2010.

3.2.2. Scenario 1 results

Emissions savings increase with market share to a maximum of 2.52% in 2020 with a biofuel market share of 10%, (Fig. 3). Overall data capture of feedstock used for biofuels, were, respectively, 89% and 73% for the Renewable Fuel Agency-2008 [34] and Renewable Transport Fuel Obligation-2010, then extrapolated [33].

3.2.3. Scenario 2 results

As shown (Table 2 and Fig. 1), the biodiesel and the bioethanol feedstock that offer the greatest savings are waste cooking oil and Sugarbeet; Consequently, the greatest emissions savings are

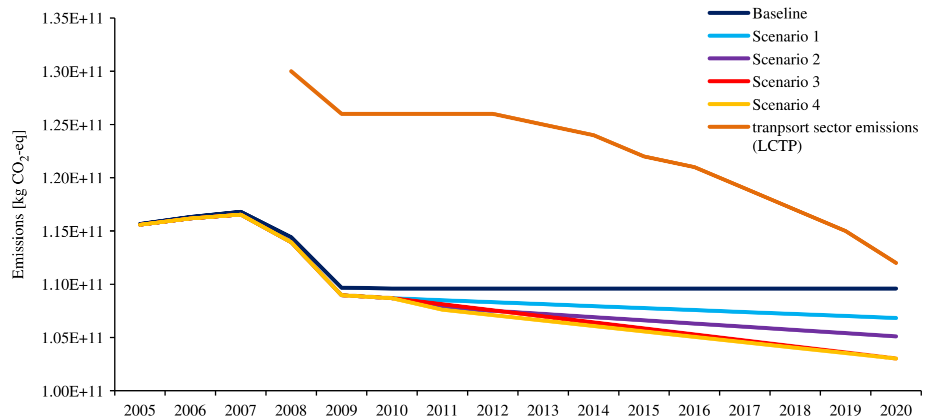

Fig. 3. Resultant emissions of scenarios, as detailed in Sections 2.3.2 and 3.2, shown against the baseline.

Table 3
Comparative table, showing both the results of this study and other LCA reference emissions.

Fuel	Feedstock	This study			Gallagher report (adapted from Frishe)[9]			EU directive 2009.28.EC [1]		
		LCA emissions/kg CO_2-eq/GJ	Country code	Savings [%]	Maximum LCA emissions/kg CO_2-eq/GJ	Minimum LCA emissions/ kg CO_2-eq/ GJ	Country code	Typical LCA emissions/kg CO_2-eq/GJ	Default LCA emissions/ kg CO_2-eq/ GJ	Default savings [%]
Bio-diesel	Soybean	54.1	CH	+38	101	51	BR	50	58	+31
	Rape	91.5	RER	−5%	260	117	EU	46	52	+38
	Palm	58.0	MY	+33	84	45	ID	54	68	+19
	Waste cooking oil	11.7	FR	+89	–	–	–	10	14	+83
Fossil Ffuel	Diesel	87.2	CH	–	–	–	–	–	83	–
	Petrol, unleaded	95.0	RER	–	–	–	–	–	83	–
Bio-ethanol	Sugarcane	43.1	BR	+55	48	36	BR	24	24	+71
	Sugarbeet	33.5	CH	+65	–	–	–	33	40	+52
	Corn	95.0	US	0	129	72	US	37	43	+49

achieved by assuming these two represent all biofuel. Maximum emission savings of 4.1% are observed with a biofuel market share of 10% reached in 2020.

3.2.4. *Scenario 3 results*

A 6% emissions saving is achieved by the current feedstock mix when 23.8% of the transport fuels market is held by biofuels. This requires rapid growth, meaning the EU target of 10% would have to be exceeded in 2012 if linear growth is assumed.

3.2.5. *Scenario 4 results*

With a market share of 14.6%, savings of 6% can be achieved. As with Scenario 3, this requries growth exceeding the EU mandate, which would required $>10\%$ biofuel market share from 2016.

4. Discussions

4.1. *LCA results*

From the results, it is apparent that differing feedstock for biodiesel and bioethanol offer different degrees of emission reduction and therefore feedstock has enormous impact on potential emissions savings. Rape exemplifies how increased emissions are possible from biofuel use, the cause of which can be hypothesised. The potential for emissions savings from first generation biofuel is highlighted by the sugarbeet and waste cooking oil feedstock. These feedstock show savings of 65 and 89%, respectively, meaning emission savings from biofuels can be significant enough to contribute towards emissions reduction targets.

Evidently, the greatest differential between feedstock LCA emissions is attributable to process emissions (Refer to Fig. 1). Noteworthy contributions are from fertilizer intensity, energy density of crop and chemical usage within the process LCA system. An example of a significant impact, as shown by Acquaye et al. [29], would be phosphoric acid for the trans-esterification process in rape biodiesel production. Another noteworthy variation between LCAs is iLUC, these differences stem from hectares of land areas required for cultivation between feedstocks.

On comparison with published LCA emission data (Table 3), it is apparent that literature values vary and therefore agreement is very dependent on feedstock and dataset. As observed from Table 3, rape feedstock shows the greatest contrast with all other datasets. Similar savings with respective to EU Directive 2009 figures were calculated for waste cooking oil and sugarbeet feedstock, with sugarcane and corn showed considerably reduced emission savings. Gallagher et al. [10] provide maximum and minimum emission scenarios accounting for land-use change, which compare well with calculated values. Calculated values are within Gallagher et al.'s [10] range near the centre (mid-point), with the exception of rape feedstock which is notably below the minimum value. Rape's irregular calculated emissions can be explained by the significant higher process emissions from the process dataset used within this study.

Process data was obtained from ecoinvent with allocations already performed. Material flows were allocated by nominal

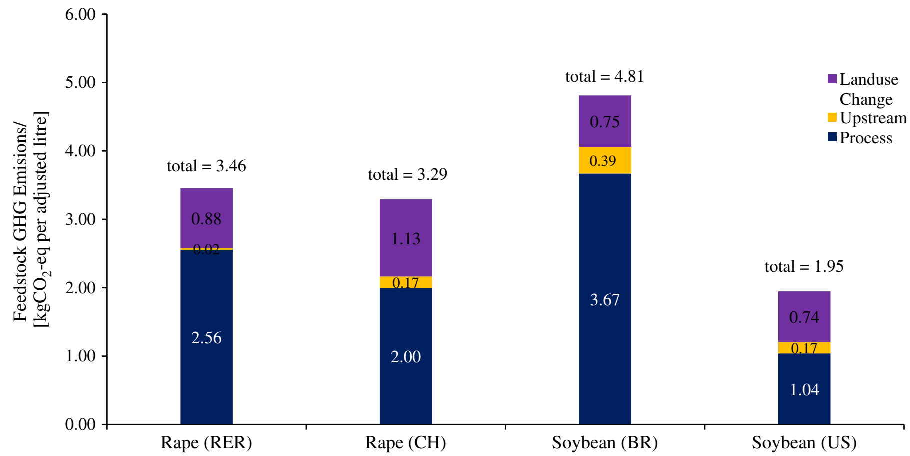

Fig. 4. Comparative table, showing different dataset locations and their respective GHG emissions.

economic values, resulting in decreased attributed downstream consumptions for processes that offer co-product production. Implications of this are that processes that offer co-products, such palm oil milling producing palm kernel oil and meal, are ascribed with less of iLUC and processing impacts. Emissions were allocation by carbon balance; meaning, the distribution is arguably infallible as resultant carbon release is finitely linked to carbon content. Because co-products share in the emissions impact, it results decreased individual product emissions and yielding favourable LCA emission profiles.

Choice of dataset for the processing can have a considerably impact on a particular feedstock emission profile; this is demonstrated by different dataset for soybean and Rape in Fig. 4. Spatial differential can plausibly be attributed to technology difference, availability and geographical use of data. The rape RER dataset is based in Europe, with a global context [30]; however, the CH dataset is European country specific and therefore considered more relevant to this study and preferentially used. It is worth noting the impact of country sourcing as a result of geographical and technological differences on resultant emissions—as highlighted by previous studies [43–45] who showed that differences can be expected between local and non-local industrial processes with regard to their environmental loads. This may have influence on the overall lifecycle results; for example, Ciroth [45] estimated a coefficient of variation of 0.2 for GHG emissions due to geographical differences in a typical LCA study.

4.2. LCA system

The use of the hybrid LCA ensures that the MRIO framework is used to capture and estimate otherwise missed inputs in the process LCA system. For example, in this study infrastructure related activities such as construction of commercial buildings (to account for construction of plants and related buildings), service related inputs (such as administration and business related activities), other special purpose machinery or agriculture machinery sectors – depending on whether the system was fossil or bio-fuel – were captured because of the robustness of the hybrid LCA system. This approach captured more than just the directly related emissions and exemplifies the strength of hybrid LCA in accounting for embodied indirect emissions. In the input–output framework used, the technological coefficients describing the production of biodiesel, bioethanol and fossil fuel do not change but their final demand changes year-on-year. Upstream emissions were of the same order of magnitude when considered as kg CO_2-eq per kg of fuel, except waste cooking oil. It is unsurprising that waste cooking oil has relatively lower upstream emissions due to its relatively short supply chain. The higher upstream emissions within petrol production, relative to diesel, could be resultant of the significant heavy and precious metals used within the refinery process. As shown by Wiedmann et al. [26], by employing the hybrid LCA, technology-specific processes in the biofuels and fossil fuels LCA systems are integrated in a generalised environmental-economic, multi-region input–output modelling framework in order to include economy-wide indirect GHG emissions in the biofuel supply chain.

The stark difference in emission savings achieved by different biofuel feedstock illustrates the necessity to gain a high data capture of feedstocks. The two market share data sets available informed which feedstock LCAs were undertaken, but the availability of datasets was the limiting factor; the unavailable datasets which had a greatest effect on the results were tallow biodiesel and more significantly wheat bioethanol. The study achieved a data capture of 89% and 73%, by volume, for the Renewable Transport Fuel Obligation (2005–2008) and Renewable Fuel Agency datasets (2008–2009), respectively.

4.3. Relevance to legislation

LCA as an environmental assessment technique has been used in energy, emissions and climate change policy discussions and in the implementation of policies such as The EU Renewable Energy Directive (RED) [46], Renewable Fuel Standard [47] and Low Carbon Fuel Carbon Standards [48] because it provides evidence of the overall environmental burden of products and processes, hence used as a decision support tool. This paper demonstrates the development of scenarios for the assessments of emissions reduction targets using LCA.

It was determined that the best case scenario for biofuel usage in achieving optimum emissions reduction in the UK transportation system is through the use of waste vegetable oil for biodiesel production and sugarbeet for bioethanol production. Currently, biodiesel from waste cooking oil constitutes circa 26% of total biofuel (or 43% of total biodiesel) market share in the UK. Sugarbeet bioethanol on the other hand makes up circa 6% of total biofuel (or 15% of total bioethanol) market share in the UK. If the market shares of waste cooking oil biodiesel and sugarbeet bioethanol can be optimised, it would offer the biggest potential for biofuel to aid the UK emission reduction targets as shown by Scenario 2. Biodiesel from waste cooking oil offers additional benefit by not competing directly with food although demand for this feedstock from other sectors such as animal feed or other chemical processing sectors may drive up the price of the feedstock.

It has been well established that indirect effects such as indirect land use has impacts on biofuel production systems; this has led to

regulatory agencies incorporating the associated emissions into the LCA of biofuels. Indirect effects on biofuel systems however is not limited to indirect land use change as economy-wide indirect requirements of the biofuel supply chain also contributes to the total GHG emissions of biofuels. This paper argues that quantitative assessments which inform policies should therefore use models or develop appropriate methods that can also account for these other indirect emissions so that a holistic approach in understanding the environmental profile of biofuels is achieved.

4.3.1. *Improvements and further work*

Although the most up to date available LCA data on biofuel production has been sourced, it may suffer from temporal delay and emission intensities may be liable to improvement through efficiency/energy sources within production. Hence, extending this work to include projections on the dynamism in the technological changes (described by changes in the IO sector coefficient) over time would be worth exploring. Data capture for biofuel market share between 2008 and 2009 from the Renewable Transport Fuel Obligation was 89% and Renewable Fuel Agency 73%. These can be improved as new data on market shares and production and consumption becomes available. Impacts of 2nd generation biofuels should also be integrated in the work as their production become commercially viable.

5. Conclusions

The lifecycle emissions of biodiesel (soybean, palm, rape, waste cooking oil) and bio-ethanol (sugarcane, sugarbeet, corn) and fossil fuel (diesel and petrol) were undertaken using hybrid LCA methodology where by technology-specific processes in the biofuels and fossil fuels LCA system is integrated in a generalised 2-region (UK and Rest of the World) environmental-economic input–output framework in order to include indirect GHG emissions in the biofuel and fossil-fuel LCA systems. The results were used to develop scenarios to assess the potential for biofuels to aid the UK towards achieving emissions reduction policy targets. The choice of feedstock for biofuel production has varying degrees of emissions reduction compared to fossil fuel; hence feedstock market share has enormous impact on potential emissions savings. Biodiesel production from waste cooking oil and bioethanol from sugarbeet offer the best case scenario in terms of emissions savings relative to fossil fuel substitutes. It was also determined that to achieve a 6% reduction emission saving from transportation as a result of the use of biofuel in the UK transportation system as outlined in the UK Low Carbon Transition Plan, under current feedstock mix, an estimated 23.8% of the transport fuels market should be held by biofuels. This would require accelerated growth meaning that the 10% EU target would have to be exceeded in 2012 if linear growth is assumed. The paper demonstrates the use of robust quantitative methods to assess emissions targets and to inform environmental policies and decision.

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